Europa Mission Update: Beyond Payload Selection

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Abstract—**Europa, the fourth largest moon of Jupiter, is believed to be one of the best places in the solar system to look for extant life beyond Earth. The 2011 Planetary Decadal Survey, Vision and Voyages, states: "Because of this ocean's potential suitability for life, Europa is one of the most important targets in all of planetary science." Exploring Europa to investigate its habitability is the goal of the planned Europa Mission. This exploration is intimately tied to understanding the three "ingredients" for life: liquid water, chemistry, and energy. The Europa Mission would investigate these ingredients by comprehensively exploring Europa's ice shell and liquid ocean interface, surface geology and surface composition to glean insight into the inner workings of this fascinating moon. In addition, a lander mission is seen as a possible future step, but current data about the Jovian radiation environment and about potential landing site hazards and potential safe landing zones is insufficient. Therefore an additional goal of the mission would be to characterize the radiation environment near Europa and investigate scientifically compelling sites for hazards, to inform a potential future landed mission.**

The Europa Mission envisions sending a flight system, consisting of a spacecraft equipped with a payload of NASA-selected scientific instruments, to execute numerous flybys of Europa while in Jupiter orbit. A key challenge is that the flight system must survive and operate in the intense Jovian radiation environment, which is especially harsh at Europa. The innovative design of this multiple-flyby tour is an enabling feature of this mission: by minimizing the time spent in the radiation environment the spacecraft complexity and cost has been significantly reduced compared to previous mission concepts. The spacecraft would launch from Kennedy Space Center (KSC), Cape Canaveral, Florida, USA, on a NASA supplied launch vehicle, no earlier than 2022. The formulation and implementation of the proposed mission is lead by a joint Jet Propulsion Laboratory (JPL) and Applied Physics Laboratory (APL) Project team.

In June 2015, NASA announced the selection of a highly capable suite of 10 scientific investigations to be flown on the Europa Mission. In the year since, the Europa Mission Team has updated the spacecraft design in order to fully accommodate this instrument suite – a significant challenge. The team is currently preparing for the System Requirements Review and Mission Definition Review (scheduled for January 2017), and is expected to mark the transition from the concept development phase to the preliminary design phase of the mission. This paper will describe the progress of the Europa Mission since 2015, including maturation of the spacecraft design, requirements, system analyses, and mission trajectories.

TABLE OF CONTENTS

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1. INTRODUCTION

Scientific motivation for studying the habitability of Europa remains unchanged, focusing on the likely existence of a saltwater ocean beneath its icy shell and potential interaction of that ocean with a rocky mantle beneath. Discussion of the scientific motivation for in situ study of Europa was presented in [1], and a brief summary of updates to that scientific baseline is presented here.

Since publication of the previous paper, irradiation tests of certain salts on earth show that these salts change color in a way that is consistent with observed "gunk" on Europa [2]. This provides support for the idea that similarly salty water from Europa's putative ocean finds its way to the surface where it is exposed to radiation, suggesting that chemical analysis of these salt compounds could tell us what is in the oceans below.

Update on plumes—The search for confirmation of plume observations from [3] continues, and other observations [4] using different methods have recently provided further tantalizing suggestions of the existence of plumes. Confirmation of currently active plumes on Europa would only increase the scientific case for studying this moon, but the case is already strong enough without plumes.

Investigations selected—In June 2015 NASA selected a suite of 10 highly capable investigations to investigate the habitability and astrobiological potential of Europa. "Habitability" includes confirming the existence of an ocean, characterizing any water within and beneath Europa's ice shell, investigating the chemistry of the surface and ocean and evaluating geological processes that might permit the ocean to possess the chemical energy necessary for life. Figure 1 shows a summary of these investigations and a mapping to the selected payloads.

Since selection, the Europa Mission Team has updated the spacecraft design in order to fully accommodate this instrument suite – a significant challenge. The team is currently preparing for the System Requirements Review (SRR) and

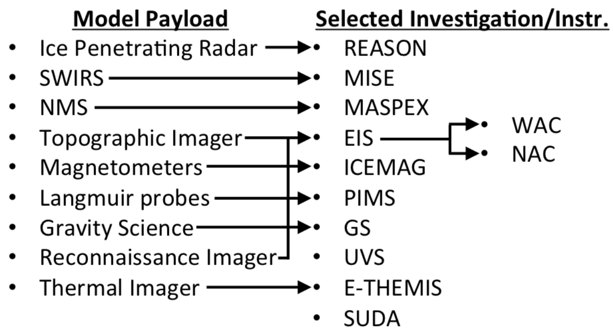

Figure 1. **Selected Instruments vs. Model Payload**

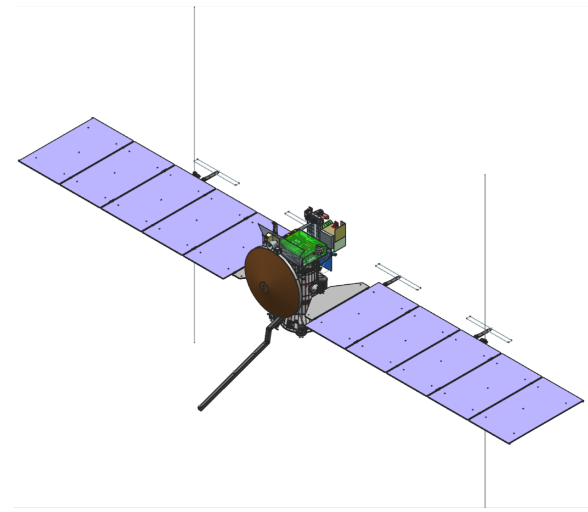

Figure 2. **Current Configuration**

Mission Definition Review (MDR) (scheduled for January 2017), which, if successful, will mark the transition from the concept development phase to the preliminary design phase of the mission.

A Europa Lander is now also in the formulation phase and would be a separate spacecraft envisioned for launch at least a year after the Europa Mission launches. While the proposed Lander mission itself is beyond the scope of this paper, the Europa Mission would support the Lander by providing reconnaissance data for landing site selection, and by providing a backup capability for relaying the Lander data back to earth in case the primary Lander-mission-provided capability were to be unavailable.

2. MISSION OVERVIEW

The Europa Mission intends to send a flight system consisting of a spacecraft armed with highly capable payload of 10 scientific investigations to orbit Jupiter and repeatedly execute close flybys of Europa. The NASA selected science instrument suite will be discussed in detail later in this paper. The prime mission spans approximately 3.5 years, allowing for the 40-45 Europa flybys necessary to achieve science objectives and priorities as specified in the 2011 National Research Council Decadal Survey [5]. The flight system (current configuration shown in Figure 2) would launch from Kennedy Space Center, Cape Canaveral, Florida, on a NASA-supplied launch vehicle. The spacecraft would be operated by a ground system, consisting of a Mission Operations System (MOS) containing a Ground Data System (GDS), responsible for command and control of the spacecraft as well as receipt, storage and dissemination of collected science data.

Science Objectives

The science objectives for the Europa Mission remain strongly grounded and consistent with planetary science objectives defined in the NASA Planetary Decadal studies [5] and with recommendations from the Europa Science Definition Team and the Outer Planets Assessment Group [6]. The level one Europa Mission objectives have been refined only slightly with the NASA selection of the Europa Mission science investigations. Due to recently reported observations of plume activity on outer planet bodies (e.g., Enceladus plumes observed by Cassini [8]) the Mission objectives have been augmented with an objective to observe potential plume activity on Europa.

These science objectives are categorized in priority order as:

1. Ice Shell and Ocean: Characterize the ice shell and any subsurface water, including their heterogeneity, ocean properties and the nature of surface-ice-ocean exchange. Map the vertical subsurface structure beneath $\geq$50 globally distributed landforms to $\geq$3 km depth *to understand the distribution of subsurface water and processes of surface-ice-ocean exchange.* Constrain the average thickness of the ice shell, and the average thickness and salinity of the ocean, each to $\pm$50%.

2. Composition: Understand the habitability of Europa's ocean through composition and chemistry. Create a compositional map at $\leq$10 km spatial scale, covering $\geq$70% of the surface *to identify the composition and distribution of surface materials.* Characterize the composition of $\geq$50 globally distributed landforms, at $\leq$300 m spatial scale *to identify non-ice surface constituents including any carbon-containing compounds.*

3. Geology: Understand the formation of surface features, including sites of recent or current activity and characterize high-science-interest localities. Produce a controlled photomosaic map of $\geq$80% of the surface at $\leq$100-m spatial scale *to map the global distribution and relationships of geologic landforms.* Characterize the surface at $\leq$25 m spatial scale, and measure topography at $\leq$15-m vertical precision, across $\geq$50 globally distributed landforms *to identify their morphology and diversity.* Characterize the surface at $\sim$1-m scale to determine surface properties, for $\geq$40 sites each $\geq$2 km x 4 km.

4. Recent Activity: Search for and characterize any current activity, notably plumes and thermal anomalies, in regions that are globally distributed.

Selected Instruments

The payload selected by NASA [7] is composed of a highly capable suite of instruments that not only meets the original set of Europa Mission science objectives, but exceeds them: the payload contains two more instruments in addition to the original eight that were assumed in the notional payload and responds to the updated science objectives (that now include the search for plumes ejected from the surface of Europa and an analysis of dust particles in the area of Europa). See Table 1 for details on the total payload resources. The selected

Table 1. Payload Resource Allocations

Resource	Allocation
Mass	310 kg
Survival Power	75 W
Orbital Energy	39700 Whrs
Flyby Energy	13700 Whrs

instruments are described in the following paragraphs, and Table 2 (following the instrument descriptions) shows instrument providers.

Radar for Europa Assessment and Sounding: Ocean to Near-Surface (REASON)— REASON's science objectives are to characterize the distribution of shallow subsurface water and structure of the ice shell; search for an ice-ocean interface; and correlate surface features, subsurface structures, and geological processes. REASON is a dual-frequency sounder with a 60-MHz band with 10-MHz bandwidth for shallow sounding, and a 9 MHz band with 1-MHz bandwidth for deep sounding. REASON's 60MHz band is divided into two receiving channels for interferometry to remove clutter along the off-nadir portions of the swath. This technique reduces or removes the need for supporting cross-track topography imaging. Projected REASON performance capabilities include 10 m vertical resolution depth sounding from 300 m to 4.5 km, and 100 m vertical resolution from 1 to 30 km.

Europa Imaging System (EIS)—EIS is a dual-system camera, consisting of a wide-angle camera (WAC) and a narrow-angle camera (NAC). The science investigations EIS would perform include investigation of geologic structures and processes, correlation of surface features with subsurface structure and possible water, studying the ice shell thickness and ocean interface, and identifying scientifically-compelling landing sites, as well as producing digital terrain models for use in decluttering REASON data. The measurement requirements consist of imaging the moon in the visible spectral range, including near-global coverage at 50 m-resolution or better for 95% of the surface.

The WAC field of view (FOV) is 48° crosstrack by 24° alongtrack, for a resolution of up to 11 m/pixel at 50 km altitude. It can operate in both mono or pushbroom stereo mode. The WAC has 6 filters for color imaging.

The higher-resolution NAC, with its 2.3° by 1.2° field of view, is a 2-axis gimbaled instrument, with a 60° range of motion in each axis, enables more coverage of the moon without changing the orientation of the spacecraft. The NAC can also produce stereo imagery with a resolution of 0.5 m/pixel at 50 km of altitude.

Europa Ultraviolet Spectrograph (Europa-UVS)— Europa-UVS hunts for and uniquely characterizes plumes erupting from Europa's surface. UVS would also investigate the composition and chemistry of Europa's atmosphere and surface and study how energy and mass flow around the moon and its environment.

The instrument is a sensitive imaging spectrograph that can observe in a spectral range of 55 nm to 210 nm and can achieve a spectral resolution of $<$0.6 nm full width at half maximum (FWHM) for a point source and a spatial resolution of 0.16° through its airglow port and 0.06° through its high spatial resolution port. This high-heritage instrument is an integrated unit with co-located electronics and sensor optics. The instrument does not contain a scan mirror, so the spacecraft must provide the maneuvering capability necessary to obtain complete spatial images of the moon.

SUrface Dust Mass Analyzer (SUDA)— SUDA detects and characterizes small particles in the atmosphere around Europa, allowing an analysis of the composition of the particles ejected from the surface of the moon. SUDA can capture up to 40 particles per second at closest approach. The instrument measures not only the density and composition of particles, but also the velocity, allowing backtracking to the originating surface position of materials, and thus to a mapping of the surface composition.

Mapping Imaging Spectrometer for Europa (MISE)—MISE acquires data enabling spectral analysis of the composition of the surface of Europa, including the presence of organic compounds, acid hydrates, salts, and other materials germane to assessing the habitability of the ocean on Europa. MISE data would also enable the investigation of the geologic history of Europa and characterization of currently-active geologic processes. The instrument would produce images at better than 25 m/pixel resolution in close flybys, at 300m/pixel resolution at higher altitudes, and at 10 km/pixel resolution for global-scale analysis.

MISE has a spectral range of from 800 to 5000 nanometers with a spectral resolution of 10 nm. It has FOV of 4.3° in cross-track, and from 0.75° to 4° (one pixel) in along-track. It also has a $\pm$30° along-track scan mirror.

To maintain detectors at the necessary cryogenic temperatures, the instrument is using a cryogenic 2-stage radiator, which requires views of cold sinks.

Europa Thermal Emission Imaging System (E-THEMIS)— The Europa Thermal Imaging System (E-THEMIS) is a 3-band Infrared imager with variable line integration times to optimize the sensitivity during the approach to Europa. The detector is an uncooled microbolometer array with 3 filters integrated in front of the detector to define the three observational bands: 7-14μm, 14-28 μm, and 28-70 μm. The E-THEMIS imaged field of view is 5.7° cross-track and 4.3° along-track.

E-THEMIS would detect and characterize thermal anomalies on the surface that may indicate recent active venting or resurfacing on Europa. It would also determine the regolith particle size, block abundance, and sub-surface layering for landing site assessment and surface process studies, and it would identify active plumes.

E-THEMIS would image the Europan surface at a resolution of 5 x 22 m (including spacecraft motion) from 25 km altitude, with a precision of 0.2 K for 90 K surfaces and 0.1 K at 220 K, with an accuracy of 1-2.2 K from 220-90 K. The instrument would obtain images with up to 360 cross-track pixels with a 10.1 km wide image swath from 100 km.

MAss Spectrometer for Planetary EXploration/Europa (MASPEX)— The MASPEX instrument is a neutral mass-spectrometer that would determine the chemical composition, especially the distribution and density variations of major volatiles and key organic compounds, of the Europa atmosphere and exosphere through multiple flybys at altitudes $<$ 1000 km.

The instrument contains a multi-bounce time-of-flight (MBTOF) mass spectrometer with a closed ion source, pulsers, a detector and associated electronics. MASPEX can classify particles with masses in the range 2 – 1000 Daltons with mass resolution (which varies with integration time) from about 7000 to 24000.

Interior Characterization of Europa using Magnetometry (ICEMAG)—ICEMAG is a four-sensor magnetometer composed of 2 flux gate (FG) sensors and 2 scalar-vector helium (SVH) sensors. The sensors are spaced along a 5 m long boom extending from the spacecraft. This instrument would measure the magnetic field near Europa, which is induced by Europa's movement through Jupiter's strong field. Measuring the induced field in Europa over multiple frequencies constrains the ocean and ice shell thickness to $\pm$2km, and ocean conductivity to less than $\pm$0.5 S/m. ICEMAG measures the magnetic field with an accuracy better than 1.5 nT in all three axes.

ICEMAG's data would be used in conjunction with the Plasma Instrument for Magnetic Sounding plasma measurements to better isolate the induced magnetic field from other field components caused by plasma in the Europa ionosphere.

Plasma Instrument for Magnetic Sounding (PIMS)—PIMS would measure the density, flow and energy of ions and electrons in the orbit of the spacecraft around Jupiter and especially near Europa. This instrument works in conjunction with ICEMAG and is key to determining Europa's ice shell thickness, ocean depth, and salinity by correcting the magnetic induction signal for plasma currents around Europa, thereby enabling precise magnetic sounding of Europa's subsurface ocean.

PIMS has a magnetospheric and an ionospheric mode. In the first, it can detect electrons with energies in the range 10 eV – 2 keV, and ion energies in the range 20 eV – 7 keV. In ionospheric mode, it can detect electrons and ions in the energy range 1 – 50 eV. It has an energy resolution of 10% deltaE/E, and a sensitivity of 0.5pA/cm^2 – 10^5 pA/cm^2.

PIMS is composed of two sensor heads, each hosting two Faraday cups (FCs), each with a 90-degree FOV, measuring the 1.5-dimensional velocity distribution function (VDF; a 1-D reduced distribution function plus vector flow angles as a function of energy/charge) of ions and electrons. The FCs measure the current produced on metal collector plates by charged particles with sufficient energy per charge (E/q) to pass through a modulated retarding grid placed at variable high voltage.

Key Challenges and Trade Studies

Radiation—The approach to mitigating the challenging Jovian radiation environment is described in the previous paper [1] and is still the mission baseline.

Planetary Protection—There have been no updates to the strategy for avoiding contamination of Europa since the previous paper.

Launch Vehicles and Interplanetary Trajectory Compatibility—The Europa Mission has been designed to be compatible with the Space Launch System (SLS) Block-1 and Block-1B, as well as the largest available non-SLS Expendable Launch Vehicles (ELVs), specifically the Delta IV Heavy and the Falcon Heavy (Figure 3). Due to the large variation in performance across this launch vehicle set, and to make best use of each vehicle, the Project has developed two interplanetary trajectory scenarios to deliver an equivalent flight system to the Jupiter system.

Table 2. Selected Instrument Providers

Selected Instrument	Provider
PIMS	APL
ICEMAG	JPL
MISE	JPL
EIS	APL
REASON	The University of Texas, Austin
E-THEMIS	Arizona State University, Tempe
MASPEX	Southwest Research Institute (SwRI)
UVS	SwRI
SUDA	University of Colorado, Boulder

Figure 3. Launch vehicles currently compatible with the Europa Mission.

The enormous lift capability afforded by both SLS configurations enables an Earth-Jupiter direct interplanetary trajectory (Figure 4). Due to the many benefits of the direct trajectory, namely the short time-of-flight to Jupiter (2.5 – 2.9 years) and the elimination of the flight system exposure to the inner solar system space environment well inside of 1.0 AU, this option is currently considered the baseline strategy for the flight system delivery to the Jupiter system. In addition, a two-arrival date strategy would be utilized to further increase the injected mass across a 21-day launch period. For the 2022 launch opportunity, the 21-day launch period would span June 4, 2022 – June 24, 2022.

The secondary strategy for flight system delivery to Jupiter would be to utilize a non-SLS ELV on a non-direct interplanetary trajectory that would require a number of planetary gravity assists to deliver the equivalent mass to the Jupiter System. Specifically, an Earth-Venus-Earth-Earth (EVEEGA) interplanetary trajectory would be needed in 2022 (Figure 5). The EVEEGA launch period would span May 25, 2022 – June 14, 2022, and would have an associated time-of-flight of 7.64 years and a minimum solar distance (perihelion) of 0.678 AU.

Maintaining compatibility with multiple launch vehicles–and hence different interplanetary trajectories–places additional constraints on the flight system design; for example, the

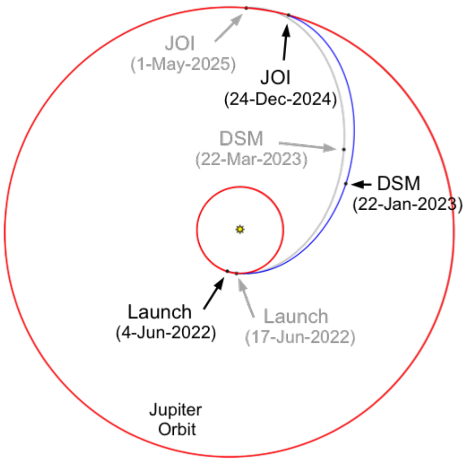

Figure 4. **2022 Europa Mission baseline interplanetary trajectory utilizing the SLS.**

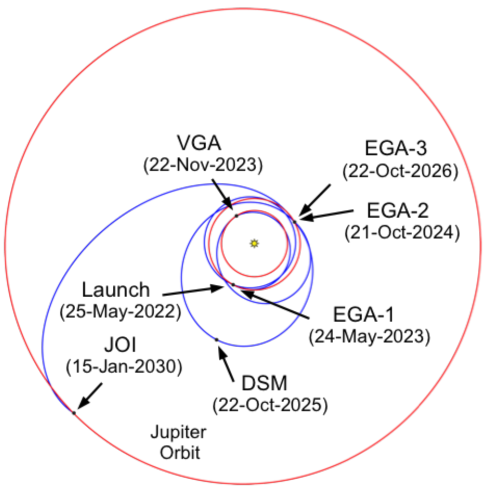

Figure 5. **2022 Europa Mission secondary interplanetary trajectory utilizing a non-SLS ELV.**

thermal subsystem must ensure survival and operation at 0.65 AU from the Sun to enable Venus gravity assists, a feature that would not be needed if only the SLS was used. The earlier a decision is made on launch vehicle, the more optimized the flight system would be, with the potential to return more science for the same or lower cost. Orbital debris compliance is not expected to differ based on launch vehicle selection, as in all cases launch vehicle stages are not left in Earth orbit. For the SLS, it is expected that the boosters and core stage would be disposed of in the Pacific Ocean, while the upper stage would be delivered onto an interplanetary orbit. A potential disadvantage of the direct trajectory is that it eliminates the availability of Earth, the Moon or Venus as potential instrument calibration targets. However, this is not seen as a major inhibitor as a number of Ganymede flybys would always be available prior to the start of the Europa science acquisition flybys.

Tour Design—The Europa Mission is predicated on the developed capability to efficiently obtain global-regional coverage of Europa (i.e., data sets at the regional scale, distributed across Europa globally) via a complex network of Europa flybys while in Jupiter orbit [9][10][11][12]. These orbits are highly elliptical, designed to minimize the time the spacecraft spends in the region of intense radiation Europa is continually immersed in. The key mission design strategy is to dip in just low enough to skirt Europa's orbit to collect a high volume of quality Europa data and then quickly escape the most intense portions of the radiation environment, thus enabling the vast majority of the orbit available to downlink high volumes of Europa data without significant radiation exposure. In addition, the time away from the harsh radiation environment (and the subsequent Europa flyby) provides margin to react to anomalies and discoveries. These benefits are not available with a Europa orbiter architecture.

The primary tour design objective of the multiple Europa flyby mission concept is to balance instrument coverage of Europa with total ionizing dose (TID), propellant expenditure (ΔV) and mission duration. The tour design attempts to maximize science return while minimizing environmental, operational and spacecraft constraints. Environmental constraints involve radiation, solar conjunctions, planetary protection requirements, eclipse durations (thermal and power implications) and potential Europa plumes. Operational constraints include, frequency of events (maneuvers and flybys), navigation feasibility, mission agility and required delivery accuracy. Spacecraft constraints include ΔV (which affect system margins), frequency of events (downlink margins, onboard storage, battery sizing, etc.), duration and location of eclipses and flyby velocities.

The current reference science tour (referred to as 15F10) stems from a 2022 Earth-Jupiter direct trajectory, consists of 42 Europa, 4 Ganymede and 8 Callisto flybys over the course of 3.4 years, and has a TID of 2.99 Mrad.[2] The average period of each Jovian orbit is $\sim$18 days, and the typical time between Europa science flybys is 14.2 days.

On approach to Jupiter (whether via a Earth-Jupiter direct or EVEEGA interplanetary trajectory), a 300 km Ganymede flyby (Ganymede-0, G0) would be utilized to reduce the magnitude of the maneuver. Jupiter Orbit Insertion (JOI) would occur at periapsis at a range of 11.1 RJ (i.e., in the less intense outer regions of the radiation belts). The spacecraft would then perform a periapsis raise maneuver near apoapsis of a 202-day period capture orbit to counter solar gravity perturbations and target an outbound Ganymede flyby. Four Ganymede flybys would then be used to reduce spacecraft energy relative to Jupiter and orientate the spacecraft's orbit such that the relative velocity and lighting conditions at Europa would be acceptable for the selected payload instruments to collect sun-lit observations on the anti-Jupiter hemisphere of Europa. This set of Ganymede flybys is referred to as the pump-down sequence.

Mapping Europa with near global coverage with multiple flybys can be done with a series of orbit adjustments referred to as "crank-over-the-top (COT)" sequences [10]. COTs can be applied to systematically cover one hemisphere of Europa at a time. Starting from an equatorial orbit around Jupiter, COTs are a series of Europa flybys that increase the spacecraft's Jupiter centered inclination (cranking) up to the maximum inclination. If one continues to crank in the same direction, the inclination will then start to decrease, until the spacecraft's orbit plane has returned to an equatorial orbit. The result is a set of longitudinally spaced groundtracks over one hemisphere of Europa. The groundtrack direction (north to south or south to north) can be manipulated by choosing

[2] **Calculated using GIRE-2p model from G0 to last Europa flyby; Si behind 100 mil Al; spherical shell**

to place the Europa flybys for a given COT sequence at the spacecraft orbits ascending or descending node with respect to Europa's orbital plane.

Global coverage of Europa may be executed over two campaigns. The first focuses on the anti-Jupiter hemisphere of Europa[3] and the second on the sub-Jupiter facing hemisphere of Europa. With the anti-Jupiter hemisphere illuminated (based on the design of the pump-down sequence), two COT sequences are used to produce intersecting groundtracks that cover the anti-Jupiter hemisphere of Europa.

Next a series of non-resonant transfers, alternating between increasing and decreasing the orbit period are used to rotate the line-of-apsides counter-clockwise to produce alternating repeated equatorial groundtracks that occur at different Europa true anomalies and longitudes in Europa's orbit. These flybys are very useful for gravity science and provide illuminated observations of Europa's trailing hemisphere.

In order to image the sub-Jupiter hemisphere with favorable lighting conditions, the local solar time of closet approach needs to be moved to the opposite side of Jupiter. This is achieved by a series of Europa and Callisto gravity assists, which places the subsequent set of Europa flybys near zero or 24 hours local solar time, but carefully avoiding Jupiter's shadow.

Finally, two more COT sequences are utilized to cover the now sunlit sub-Jupiter hemisphere of Europa (Figure 6).

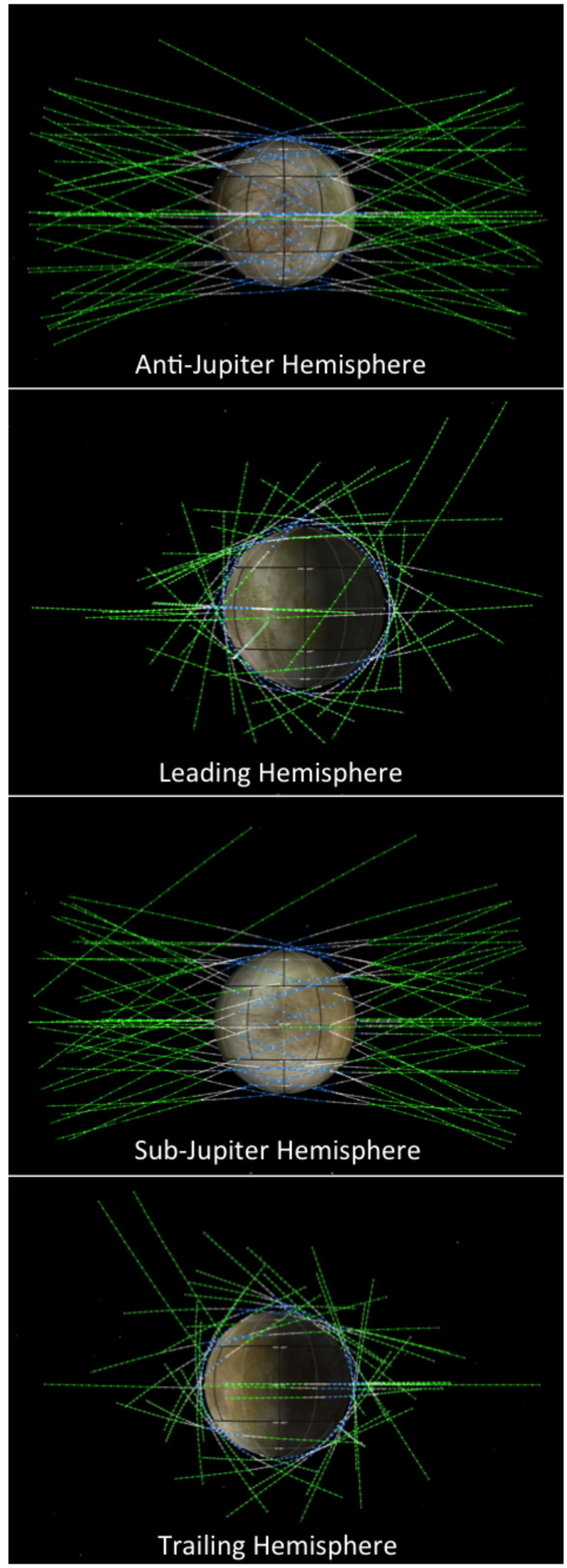

Figure 6. 15F10 tour. A network of 42 Europa flybys design to achieve global-regional coverage of Europa. (Blue: Alt $\leq$ 400 km, White: 400 $\leq$ Alt $\leq$ 1000 km, Green: 1000 $\leq$ Alt $\leq$ 4000 km)

Scenarios and Mission Operations Approach—The Europa Mission Operations approach is intended to be simple, allowing collaborative science and situational awareness of the flight system as well as Europa. Collaborative mission operations can be enabled by a single ground system architecture that includes JPL and APL Mission Support Areas (MSAs) located at both respective institutions. This provides many benefits:

- Common jointly-developed ground software, used for both MSAs. Each MSA can be enabled with the same functional capabilities (Planning, Control, Assessment, Navigation).
- Mission software applications contributed by each institution to the common ground architecture will take advantage of the best both institutions have to offer.
- Each MSA has equal access to shared data archives, testbeds, and work spaces housing mission data; access to common configuration controlled GDS software and mission models; and each could have full connectivity with external operations interfaces (i.e., DSN, instrument teams, PDS) as needed.

In addition to two primary bi-coastal MSAs, distributed Instrument operations can be performed from the instrument team home institutions – at what are being termed "i-SOCs:" Instrument Science Operations Centers. An overview of the conceptual Mission Operations System is shown in Figure 7.

Once launch has successfully occurred and the flight system has been acquired by the Deep Space Network (DSN), the mission operations team would check out the basic function-

[3]Europa is tidally locked (i.e., the same Europa terrain always has the same orientation relative to Jupiter) so illuminated terrain is simply a function of where Europa is in its orbit.

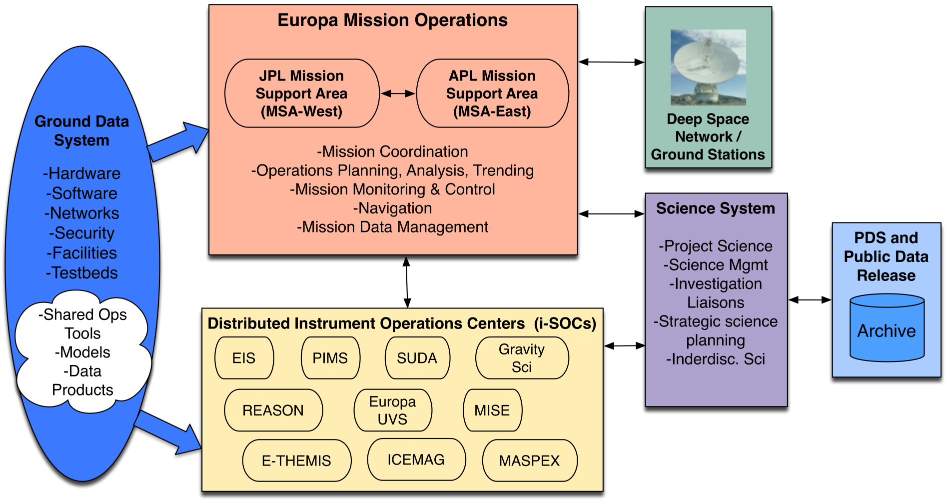

Figure 7. Conceptual block diagram of the Mission Operations System

ality and update the spacecraft ephemeris. Cruise operations are primarily focused on flight system health and safety with the occasional calibration or maintenance activity. If the mission is on an indirect trajectory, the mission operations team would coordinate and sequence any gravity assist flyby activities as needed. The JOI burn and associated flight system activities are executed by an on-board autonomous program with fault protection in place to ensure that the burn completes successfully, placing the flight system successfully into orbit around Jupiter. A series of gravity assists from Ganymede would be used to set up the first Europa campaign, about 11 months after JOI. The mission operations team would use these Ganymede flybys leading up to the science tour as practice for orbital operations – allowing the team to get some experience with a flyby of one of Jupiter's moons and characterize the behavior of the system in Jupiter's environment.

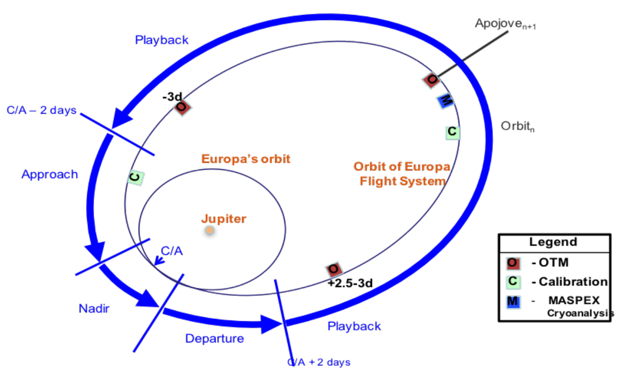

Figure 8. Phases of a Europa encounter

The Europa tour portion of the mission includes the basis of the entire science campaign, rolled up into approximately 40-45 close flybys of the moon, with some as low as 25 km above the surface. Each encounter is divided into four subphases: the approach subphase, beginning approximately two days prior to closest approach; the nadir subphase, when the spacecraft is in a nadir-pointed attitude for collaborative Europa science data collection; the departure subphase, extending from the end of the nadir subphase until about two days after closest approach; followed by a playback subphase. The phases are shown graphically in Figure 8. Most of the science data collection occurs during the approach through departure subphases, with the exception of some in-situ data collection and occasional instrument calibrations. The playback phase is primarily used for downlink of the collected data. Additionally, during each transfer, three maneuvers are executed to maintain and optimize the flight system's planned trajectory and the flyby altitude.

Operationally, there are several challenges that the mission operations team must address due to the nature of this mission, including but not limited to: the high radiation environment in which the flight system must collect science data; the long distance from earth – hence the long round-trip light time for communicating with the flight system; and the management of important shared resources such as the available solar energy and available downlink bandwidth. To this end, the ability to apply principles of operability early in the design of both the flight and ground systems will help to increase the visibility, commandability, and flexibility in how the mission operations team interacts with the flight system over the course of the mission. To date, approximately 150 requirements have been developed specifically related to the operability aspects of the design of the flight and ground systems, with the goal of reducing mission operations complexity, and thus overall operations team size and cost.

3. FLIGHT SYSTEM OVERVIEW

Spacecraft Summary

The 3-axis stabilized Europa Mission spacecraft concept incorporates a modular design, which enables concurrent work in all modules, allowing simultaneous fabrication, integration and testing, with clear schedule benefits. The modular design also helps in re-work by allowing easier access to internal subsystems. The total flight system wet mass is approximately 4000 kg, of which 2200kg is dry mass and 1800 kg is made of propellants. The total science payload mass is expected to be approximately 160 kg. The 6.36 m tall notional flight system [13] shown in Figure 2 has a mass margin of over 34% and power margin of over 40% compared to the launch vehicle and power subsystem capabilities.

Structure/Mechanical

Key changes from the configuration described in [1] are an overall reconfiguration of the vehicle configuration following the decision to use solar power, and the accommodation of the selected instruments.

Optimization of solar vehicle—It was recognized that after making the switch from Radioisotope Thermoelectric Generator (RTG) to Solar Array (SA) there had not been a concerted effort to optimize the solar vehicle. That work completed in 2015. Major changes include moving the High-Gain Antenna (HGA) to the side of the vehicle and the solar arrays closer to the center of mass. These changes are shown in Figure 9.

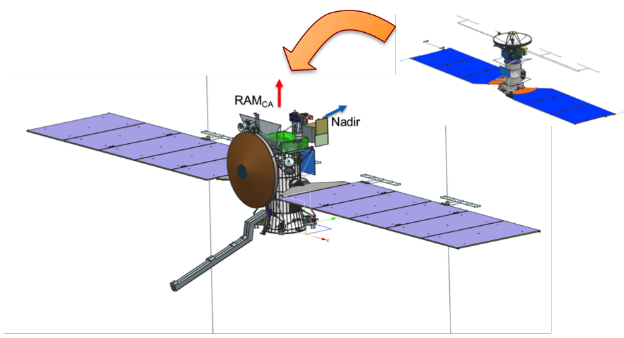

Figure 9. Evolution of vehicle configuration

Accommodation of selected payload—instrument placement and views, primary axes and flight direction have all been selected to maximize utility of the highly capable science payload. See Figure 10. This has resulted in significant but accommodatable mass growth, as allowed for in the original architecture. Dry mass of the flight system has grown from 1700 to 2200 kg.

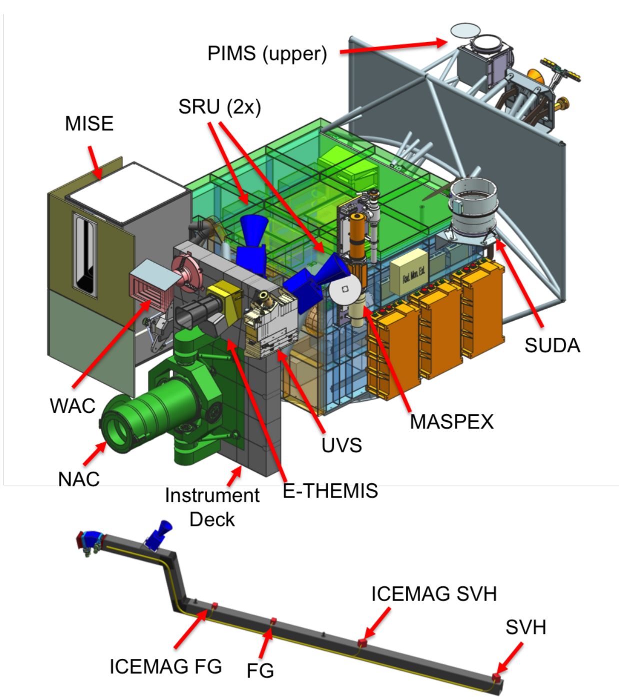

Figure 10. Selected instruments accommodations

More information about the updated mechanical configuration can be found in [14].

Selected Instrument Accommodations

As originally formulated the flight system would be powered by radioisotopes. Both Advanced Stirling Radioisotope Generators (ASRGs) and Multi-Mission RTGs (MMRTGs) were baselined at various points. The change to solar arrays occurred after a trade study determined that while there was increased complexity, solar arrays had a number of benefits including being considerably less expensive and the ability to smoothy scale the power supply (as opposed to the radioisotope supplies that come in discrete and much larger quanta). [15]

In preparation for the selected instrument accommodation the mechanical team developed a number of possible configurations. That work is fully discussed in [16] and a brief overview is provided here for context.

The three most promising configurations were labeled 2C, 2D-1 and 2D-2. In 2C the spacecraft is oriented such that the nadir direction is +Y facing while the high gain antenna is on the -Y. A table summarizing the major differences can be found in Table 3.

2D-1 and 2D-2 were developed in response to some of the known limitations of 2C, namely that in 2C the placement of the REASON antenna “behind” the SA would limit the solar array gimbaling, the electrical interactions between REASON and the SA would be hard to measure, and the REASON boom interferes with a number of instrument and radiator FOVs.

With the 2D configurations the nadir deck would be in the +Z direction. In 2D-1 the Ram direction at closest approach would +Y, and in 2D-2 the Ram direction at closest approach would be -Y. While these allowed REASON to be placed parallel to the SA (as in 2D-1), it complicates a number of issues including integration and test and access to the vault. Moreover, there are also potential issues because the SA could rotate into the FOV of several systems, including the EIS cameras, MASPEX, and MISE.

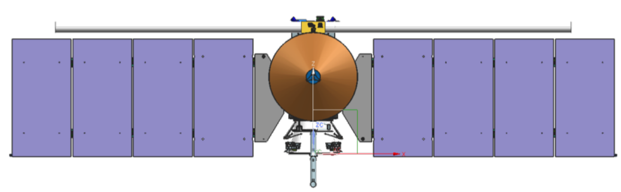

Figure 11. 2D-1 with REASON on the +Z of the spacecraft

Other configurations were also considered including a Juno like approach with nadir facing instruments on the end of the solar array, and a spacecraft with a SA that folded to clear the FOV issues during science operations. For a number of reasons these were determined to be less viable than the ones above and they were not studied more deeply.

Trade Studies with the Engineering Subsystems and Selected Instrument Teams

The next step of the process was a detailed trade activity with both the engineering subsystems and the instrument teams. Each team thoroughly assessed the pros and cons of each of the configurations, including possible mitigations and science impacts. Those discussions were used to both adjust the configurations slightly to address issues, and to also

Table 3. Configurations

Configuration	RAM at closest approach	Nadir deck placement	REASON placement
2C	+Z	+Y	+Y
2D-1	+Y	+Z	+Z
2D-2	-Y	+Z	+Z

clarify any misunderstandings regarding placement, FOVs, operations, etc.

This activity also helped identify the driving payload accommodation constraints. Many of these constraints (fields of view, radiator fields of view, co-alignment, and magnetic cleanliness, for example) were expected, allowing rapid determination of possible instrument placements that would allow for minimal disruption to other payload elements. Other payload features were more challenging, including the contamination requirements for MASPEX and SUDA and the possible microphonics generation from the MASPEX and MISE cryo-coolers. Detailed modeling is already in progress to determine the best way to mitigate any potential issues.

Although the 2D-1 configuration was the most balanced, both the instruments and subsystems generally preferred the 2C configuration. This configuration presented challenges in accommodating the MISE and REASON instruments, but it was promising enough that a separate effort was brought to bear on these issues.

MISE is best suited to the original spacecraft concept that used MMRTGs. That compact spacecraft concept had provided for clear fields of view, which is a driving requirement for the desired passive thermal design of the instrument. A detailed thermal study of the SA spacecraft by the MISE team concluded that the only way to keep a passive thermal approach was by using a Winston cone with an aperture on the order of 1m in diameter and a mass of over 70kg. But this approach was not a panacea, and in addition to the large impact on FOVs of other instruments, additional limitations (including orbital determination, lighting, and range) reduced the number of flybys that MISE would be able to collect science to unacceptably low levels, especially this early in the lifecycle of the project. Accordingly, the decision was made to go to a hybrid thermal design that uses cryocoolers.

Although initial investigations during the MMRTG/SA trade suggested that a low-frequency radar was compatible with the solar arrays, further investigation led to new requirements regarding the spacing and orientation between REASON and the SA. This is further complicated by the fact that REASON actually consists of two elements, a VHF antenna and an HF antenna, each with unique interactions with the spacecraft.

Over a dozen design variations were examined, including Yagis, booms, separate, and integrated antennas. The work resulted in a variant configuration, where the REASON antennas are on the solar array, and the REASON HF antennas now form an H shape with the solar array being the middle bar. This approach is not ideal in that it brings a complexity to the schedule, integration, and test by tightly coupling the SA to the REASON instrument. On the other hand, one of the biggest issues challenges with REASON is ensuring that the electrical environment of the spacecraft is well known. The direct physical coupling of these two systems also results in a direct electrical coupling that can be characterized.

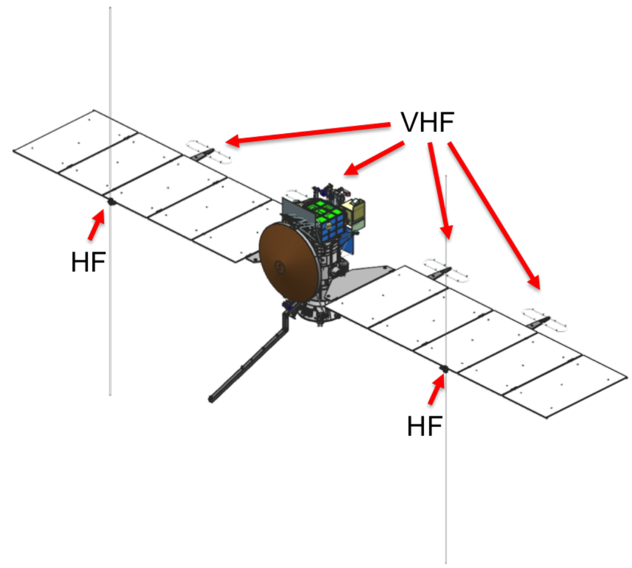

Figure 12. Updated configuration in the flyby orientation

Other challenges include potential contamination from the thrusters onto the VHF antennas; antennas moving through the FOVs of other instruments; and control, pointing, and stability. Nonetheless, this team is confident that these challenges can be addressed (including work that has already been performed to adjust the spacing of the VHF and HF antennas to reduce the FOV impacts to other instruments) and for the first time since instrument selection the Mission can be said to have a design that accommodates all the instruments.

Fault Management

Design Approach—The Europa Mission spacecraft is single-fault tolerant – no credible fault will result in the failure to achieve mission success. Block redundancy is the primary approach to mitigate single point failures; design margins will be applied where redundancy is not practical. Fault Containment Regions (FCRs) are established throughout the spacecraft to prevent the effects of a fault in one FCR from propagating and causing a loss of functionality in another. FCRs not only provide for clean fault isolation but they also provide for the ability to tolerate multiple failures in the spacecraft – an approach necessary for the long duration mission and radiation environment at Europa. Fault management algorithms/behaviors are implemented in onboard flight software to autonomously monitor unsafe conditions, execute corrective actions, and establish a safe state for further diagnosis and recovery by the ground.

Safing Response—In the event of a fault that threatens spacecraft health and safety, the safing response autonomously configures the spacecraft into a power-positive, thermally safe, and command-capable state. Additionally, the spacecraft autonomously downlinks its state to the operators on

Earth. Depending on the mission phase and the severity of the fault, different sets of hardware will be turned on or off, different pointing targets (the Sun or Earth) and different telecom configurations will be selected. While in safe mode, ground commands can be sent to increase downlink rates and provide additional diagnostic data to operators. When it has been determined that it is safe to return to normal operations, pre-defined procedures are used to exit out of safe mode.

Flyby Recovery—Due to the nature of the Europa mission in which science collection occurs during a limited set of Europa flybys in a high radiation environment, the flight system is designed to be robust to radiation-induced transient faults. A transient fault is defined as a fault that can be cleared without a power cycle of the affected component and once cleared, the equivalent functional performance of the system can be autonomously recovered. In this fail-operational strategy aimed at maximizing science collection, the flight system will attempt to recover from transient faults and resume science operations within 10 minutes, unless spacecraft health is in jeopardy. In that case, the flyby will be aborted and a safing response will occur.

Motion and Pointing

Further key changes from the configuration described in [1] are: refinement of the pointing and stability requirements with the selected instruments; replacement of main engines with smaller thrusters; and the use of larger reaction wheels to control the larger vehicle.

Pointing requirements for the selected payload are now understood and the vehicle has been updated to support them. Pointing control of 0.7 mrad is required for the UVS for measurements of Europa exosphere during stellar occulations. Pointing stability of 15mrad 3 sigma is driven by the EIS NAC. Reconstructed pointing knowledge of 0.9 mrad is driving by UVS. For telecom, Ka band pointing during science data downlink continues to require 1 mrad pointing control.

Previously, JOI was performed with one of two redundant main engines delivering $\sim$450 N of thrust. Each main engine was independently gimbaled for thrust vector control. A system trade resulted in replacement of the main engines with redundant set of eight aft facing 22 Newton engines. This provided a significant mass and power savings, a large reduction in complexity due to removal of the need for gimbaling mechanisms, and a reduction in risk of catastrophic failure from a micrometeoroid strike on the large engine bells. The main drawback, an increase in JOI burn duration is easily accommodated by the gentle gravity well of Jupiter.

Electrical Power and Energy

As noted in [17], a benefit of the solar electric power approach is the flexibility for growth. As expected, the increased demands from the selected payload have indeed caused the solar arrays to grow from $\sim$50 m^2 of solar cell area to $\sim$90 m^2 currently. 10 total panels (five on each single-axis articulated wing) are currently baselined, with an end of mission generation capacity of $\sim$650 W. The battery has also grown accordingly, from 180 to $\sim$340 Ah.

In addition, the REASON antenna suite has been integrated into the solar arrays as discussed previously.

Avionics and Data

The main changes in the avionics architecture have been selection of key interface architectures between the RAD-750 based Command and Data Handling (CDH) subsystem and the payloads (a mix of Spacewire and RS422) and between the CDH and the Radio (Spacewire). The size of the Bulk Data Storage is unchanged at 512 Gb.

Thermal

The trajectory options described previously necessitate a thermal control system that can keep spacecraft temperatures within allowable limits in both the extremely hot case of inner cruise and the cold, energy-limited environment near Jupiter and Europa. As described in [1], the spacecraft will employ active thermal control (pumped fluid loop) and some passive strategies to limit overall heat loss (such as multi-layer insulation blankets) to achieve the required performance.

As previously noted, the fluid loop is organized to make maximum use of waste heat by transporting it from the dissipating elements in the vault to the components that require external temperature control, such as the Propulsion Module and some instrument interfaces. The primary update to this design includes the addition of a Replacement Heater Block, located after the vault, which provides to the loop any further heat required for thermal control after collecting waste heat from the vault. For effective operation in the hot and cold case, a mixing valve allows variable flow through the radiator to reject more heat in hot cases but retain it in cold cases where energy efficiency is key. Use of further energy management strategies such as louvers is currently under investigation.

Maneuver and Propulsion

As mentioned earlier the propulsion system has been changed from a dual main engine design to a multi-engine design that includes a complement of 16 bi-propellant engines. The propulsion system is an all bi-propellant design providing both ΔV and attitude control capability for the Europa Mission.

The propulsion system is sized with two large tanks – one each for fuel and oxidizer – and takes into account the multiplicity of launch vehicles and interplanetary trajectories under consideration. Thermal control, as discussed previously, is provided via the pumped fluid loop to tanks, components, lines, and engines. The propulsion module comprises the bottom section of the spacecraft and provides mechanical accommodation for the tanks, lines and engines as well as mechanical accommodation for the large solar arrays. A dedicated propulsion module controller provides all electrical interfaces for the propulsion subsystem and the solar array gimbaling and deployment. Simple interfaces mechanically connect the propulsion module to the vault mounted above and to the launch vehicle adapter below.

Communications

The spacecraft communication system is mostly unchanged since NASA selected the Europa Mission instruments. A 3-m HGA is provided to return 3.3 Tbits of data during the mission using a 35W Ka-band TWTA on the spacecraft. The spacecraft also provides an X-band transmit and receive communication capability including a 20W X-band transmitter. The X-band system provides two-way communication with Earth during all phases of the mission via the HGA or with any of the antennas including a medium gain antenna, fanbeam antennas and low-gain antennas. This combination of antennas is designed to provide coverage for all phases of the mission and spacecraft orientations. The X-band communication system will also be used to provide gravity science measurements during the flybys of Europa. These Doppler measurements from the spacecraft would allow scientists to make inferences about the surface of Europa and could be used to help confirm the presence of a subsurface ocean on Europa.

4. Future Work

Assuming a successful SRR/MDR in early 2017, the project would transition into the Preliminary Design Phase culminating in the Preliminary Design Review in 2018.

5. Summary and Conclusions

Europa, the fourth largest moon of Jupiter, is believed to be one of the best places in the solar system to look for extant life beyond Earth. Exploring Europa to investigate its habitability is the goal of the planned Europa Mission. This exploration is intimately tied to understanding the three "ingredients" for life: water, chemistry, and energy.

The joint Jet Propulsion Laboratory (JPL) and Applied Physics Laboratory (APL) Project team has now been joined by the teams of the nine selected science instruments, and together they have formulated a mission and spacecraft which would revolutionize our understanding of this enigmatic and tantalizing world.

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Biography

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Kathy Schimmels *is a member of the Mission Operations Systems Engineering Group at JPL and is currently the MOS Engineering Lead for the Europa Mission. Kathy served as the MOS Engineering Lead for the Dawn Mission to Vesta and Ceres, and the NuSTAR X-ray Telescope Mission. She has over 7 years of flight ops experience in science operations and leadership during both prime and extended mission operations on the Galileo Mission. Additionally, Kathy was the lead systems engineer in the development of a multi-mission operations system model as the basis for future mission development. She received her B.S. and and M.S. degrees in Aerospace Engineering Sciences from the University of Colorado, Boulder with a minor in Astrophysical, Planetary, and Atmospheric sciences.*